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QUARTERLY PROGRESS REPORT 1

EXPLOSIVE FORMING OF CLOSURES FOR LARGE
SOLID PROPELLANT MOTOR CASES

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28 January 1963

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EXPLOSIVE FORMING OF CLOSURES FOR LARGE
SOLID PROPELLANT MOTOR CASES

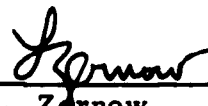
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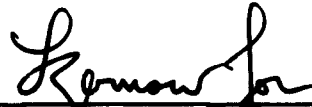
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ABSTRACT



Explosively formed 120-inch diameter heads with 37-inch and 48-inch deflection are described. Comparisons of results from free forming and ice die forming are made and the relative advantages of each are presented. Specific problem areas associated with material procurement and material handling because of the unique sizes involved are briefly described.



FOREWORD

This Quarterly Progress Report covers the work performed from 17 October 1962 through 17 January 1963 under Contract No. AF 04(611)-8395, under the cognizance of the 6593d Test Group (Development), Code DGSCH, Edwards Air Force Base, Edwards, California. This contract is under the technical direction of Lt. B. Thomas of the 6593d Test Group.

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1. INTRODUCTION

The purpose of this program is to demonstrate the feasibility of using either a free forming die or an ice die to produce two 120-inch diameter rocket motor closures by the explosive forming process. This third quarterly report describes the results obtained in the subscale and full scale tests completed during the October 1962-January 1963 period.

2. WORK SUMMARY

2.1 A series of tests completed in the 36-inch diameter subscale die were made to investigate:

- a. Air cushion effect on reducing over-forming.
- b. Maximum contour deviation which may be obtained by explosive sizing in ice die.

2.2 A total of four tests in the full scale 120-inch diameter die were completed; one test was in the free forming die; the other three tests were in the ice die. All tests were with AISI 1020 welded steel blanks. As a result of these tests, it has been concluded that a cover sandwich sheet will be used with the AMS 6434 steel blanks. Careful examination of the advisability of reducing the deflection of the formed dome from a hemispherical contour to a 1.4 to 1 elliptical contour is underway to increase the probability of successfully producing a usable closure.

2.3 The thickness pattern of an explosively formed full scale dome was compared to the changes observed in the subscale test work. Thickness changes are observed to be identical when expressed as a percentage of initial blank thicknesses with the measured points located as a ratio of the distance from the apex to the diameter of the dome.

2.4 The 185-inch diameter AMS 6434 steel blanks were received from the mill. Due to waviness in the blanks, the material was

shipped to a vendor for flattening by rolling prior to being surface machined to provide thickness contour.

2.5 Full scale AMS 6434 steel blanks have been furnished to a vendor for surface machining the required thickness pattern in the blank.

2.6 Two full scale AISI 1020 steel blanks were furnished for surface machining a desired thickness pattern.

2.7 Metallurgical examination of the AMS 6434 steel in the full scale blanks was completed to determine compliance of the mill with the specifications called out in the initial requisition. Mill Spec. MIL-S-21515A (WEPS), 1 April 1960, "Steel Plates, Sheets and Strips: Chromium-Nickel-Molybdenum-Vanadium" was used with material to meet standards for Class 2.

3. TECHNICAL DISCUSSION

Table I presents a tabulation of all test firings completed in this period.

3.1 36-INCH DIAMETER FREE FORMING

One 36-inch diameter test was made with the free forming approach to determine the capability of an air cushion to retard over-forming in the skirt area when producing a full hemisphere. The test was made with an AISI 1020 steel blank, 5/16-inch thick. A rubber tube, 20-5/8-inch O.D., 8-5/16-inch I.D. and 6-5/8-inch high, was taped securely to the plate. An explosive charge of 2,750 gms was used. The blank fractured badly, with the apex portion of the blank torn from the balance of the material. Apparently, the tube acted similarly to a hollow cavity which can produce a gas jet under proper conditions of pressure and shock, and fractured the plate prior to any appreciable forming taking place. The fractured pieces were blown to the bottom of the free forming die cylinder.

From experiences with jet behavior and the shape charge phenomena, it is suggested that a concentrated air cushion, as illustrated by the

test described above, will not solve the problem of over-forming. The air curtain approach which was examined and described in a previous report may give the solution but additional experimentation is necessary.

3.1.1 As a possible solution to over-forming in the skirt area while producing a hemisphere in the free forming die, the 36-inch diameter die will have a 6-inch wide, 36-inch diameter, cylinder welded below the draw ring. This should serve as a restraint to the blank forming beyond the hemispherical contour by guiding the material during the early stages of forming. If this technique proves practical in resolving the over-forming problem, it will be immediately applied to the full scale die.

3.1.2 The problems of over-forming with a free forming die are most severe for deep hemispherical closures. Deflections to 1.4 to 1 or 1.6 to 1 elliptical contours can be obtained without over-forming. This was graphically presented in Figure 4 of the 1st Quarterly Report. Failure to resolve the problem of overforming, in the free forming approach, may make it necessary to modify the final contour to one that is less than a hemisphere.

3.2 36-INCH ICE DIE

A series of tests were made in the 36-inch ice die to determine the ability to obtain a given contour and the reproducibility of the process.

3.2.1 Welded AMS 6434 Steel Blanks

The first set of three tests shown in Table I were made with an AMS 6434 steel blank welded as shown in Figure 1 and fired in the 36-inch diameter ice die. As a result of the first shot, the blank was formed to 18-inch depth. After stress relieving, the head was explosively sized with a measured maximum contour deviation from a hemisphere of 3/8-inch. After a second sizing shot, the measured deviation was reduced to .125-inch.

3.2.1.1 While the results in reduced contour deviations are encouraging, the ability to explosively form high strength welded blanks to the depth accomplished in these tests is extremely promising. In any extension of the fabrication process to larger

missile closures, it will not be possible to procure steel blanks from the mill in the diameters required. The ability to form welded blanks will allow explosive forming to be given primary consideration as a fabrication process for the larger missile closures which are in the planning stages.

3.2.1.2 Visual observations of the weldments after forming show no indications of fracture. X-ray and magnaflux of the welds to insure that they have not been adversely affected will be made.

3.2.2 AMS 6434 Steel Blanks

In an effort to reduce the contour deviation below the .125-inch obtained above, additional tests were made with the high strength steel alloy without welds. As a result of these tests, the following observations were made:

3.2.2.1 When sizing a formed head in an ice die, it is necessary to pre-cool the head below 32°F to prevent melting on the surface of the ice cavity and distortion of the cavity contour.

3.2.2.2 In the second firing for HS 1/4-2, the flat apex and over-formed skirt area were due to ice melting in the cavity wall and filling and flattening the apex contour. In the second firing for HS 1/4-3, the dome was cooled by solid CO₂ prior to placing into cavity. However, the flange and mouth area were not adequately cooled and some melting did take place in this area, allowing for over-forming in the mouth of the die. In Test HS 1/4-5, the head was packed with solid CO₂. As a good vacuum could not be obtained and the leak was not located, the head was sized with no vacuum. The air apparently compressed behind the head as it was sized and ejected the unit from the die when the pressure was released. In the course of being forced from the die in the second sizing shot, the head was deformed so that it could not be replaced.

3.2.2.3 The inability to produce a vacuum was found to be a defective seal between the die body and the bottom plate. This seal is in process of replacement.

3.2.3 Ice Die Tests

Test No. HS 1/4-4 illustrates a specific weakness in the ice die which is not present in the normal hard die approach. The head which was formed in this test showed wrinkles in the mouth and knuckle areas. Normally, where a tendency toward wrinkling is seen when using hard dies, the

wrinkling is forced into the I. D. of the part and a subsequent sizing operation will eliminate these wrinkles. With the ice die, however, the concentrated pressure over a small area as represented by the wrinkle will deform into the ice wall, deforming the ice cavity while producing a part which cannot be replaced into a cavity with the appropriate contour. Thus, it may be concluded as a basic principle, that for materials and dimensions where some wrinkling may be anticipated and which may normally be ignored in hard dies, this wrinkling must be given consideration when using ice dies and the appropriate steps taken to eliminate the tendency to wrinkling by whatever steps are necessary.

3.3 FULL SCALE TESTS

Three AISI 1020 welded steel blanks were tested in the full scale die. The weld pattern is shown in Figure 1.

3.3.1 Test F-1

Test F-1 (Table I) was made in the 120-inch free forming die with a welded blank of 1/2-inch thick AISI 1020 steel plate. An explosive charge of 12,100 gms with a 15-inch standoff formed the blank to a depth of 37-1/2-inch with no wrinkles as shown in Figure 2.

Strain and thickness measurements were made and are plotted in Figures 3, 4 and 5 and are tabulated in Tables II and III. The closure was then stress relieved in preparation for the second firing. As the closure had not overformed in the knuckle area with the depth attained, it was decided to perform the second firing in the ice die to control the contour in that area. Scallops were torch cut in the flange of the closure to relieve compression strains in the periphery and allow easier draw-in of the material. The scallops were 8 inches wide, 12 inches deep and 12 inches apart completely around the closure. A complete sequence of photographs of the second firing show the operations involved in using the ice die. This sequence is shown in Figures 6 through 22. In the second firing, the dome was formed to a depth of 48-1/2 inches, a gain of 11 inches over the first firing. The condition of the die and ice were excellent after the firing.

3.3.1.1 The strain pattern and thickness changes in the formed 120-inch diameter head which result from the explosive forming process are very similar to those obtained in the 36-inch diameter configuration which were previously reported in the 1st and 2nd Quarterly Progress reports for related depths of deflection. This

similarity of pattern, irrespective of size of part, is of considerable value in being able to extrapolate to larger closures.

3.3.1.2 Due to limitations in die strength, where the AISI 1020 steel is below the brittle transition temperature in the ice die, it is considered advisable to limit the explosive charge to the quantities which have been used. However, with the charge size limitation, the head produced in two successive forming shots with the intermediate stress relief still exceeds a 1.4 to 1 elliptical contour.

3.3.1.3 Visual examination of the weldments in the head showed no detrimental effects resulting from the two successive forming shots.

3.3.1.4 The contour of the formed head will be accurately measured and the relationship of the contour to a 1.4 to 1 ellipse will be established. The head will be trimmed and sized to a hemispherical contour and maximum deviations from a hemisphere will be obtained.

3.3.1.5 The sequence of photographs (Figures 6 through 22) for the 120-inch diameter die show the following:

- Figure 6. The complete refrigeration system and die orientation to the system are shown in relation to the explosive forming area.
- Figure 7. Shows the plastic hemispherical mold being removed from the die after the ice has been frozen.
- Figure 8. Shows the ice die cavity and the frost being removed from the draw ring.
- Figure 9. The partially formed head (37-1/2 inches deep) being prepared for placing into the die cavity.
- Figure 10. The dome is lowered into the die cavity.
- Figure 11. The hold-down ring is assembled to the die and the partially formed dome.
- Figure 12. The clamps are assembled to the die draw ring and hold-down ring.
- Figure 13. The ice die is gently lowered into the water-filled forming pit. It will be noted that the explosive container is empty and assembled to the die.

- Figure 14. The liquid explosive is poured into the container while the die is suspended above the forming tank.
- Figure 15. The water spray is the result of the shock wave passing from the water to the air. A secondary pulse, where the gases vent from the water surface is not shown in this sequence.
- Figure 16. The forming die is removed from the forming tank and tilted to allow the water to flow from the die cavity.
- Figure 17. The water is all removed from the die cavity and the formed head is seen in the die.
- Figure 18. The formed head is lifted from the die.
- Figure 19. The interior view of the formed head is shown with the weld area seen in the upper center of the head.
- Figures 20 through 22. Show three views of the head after the second forming. Very slight wrinkling in the area over the draw ring may be noted. Had the forming gone to any greater depth, it could be anticipated that the wrinkling would become more severe.

3.3.2 Tests F-2 and F-3

Tests F-2 and F-3 were made with AISI 1020 blanks which were to be surface machined to a thickness pattern which was calculated to give a uniform thickness in the formed dome. As will be described, both blanks failed due to fracture which is mainly ascribed to the high brittle transition temperature for this material. Some attempt to elevate the blank temperature prior to firing was made by holding the die assembled with the blank in the water-filled forming tank, allowing the blank to reach a steady state temperature with the water. From the difficulties as will be described below for Tests F-2 and F-3, it is questionable that this approach was very successful in raising the blank temperature above the brittle transition temperatures.

Waves in the AISI 1020 steel plates made it difficult to machine to the tolerances required. The first machined plate (F-2) was approximately

.020-inch undersize and the second plate (F-3) was as much as .060-inch undersize in some areas. This represents 33 per cent of the desired thickness in the apex portion of the plate. A comparison of the desired thicknesses and the machined thicknesses is shown in Table IV.

3.3.2.1 The first contour machined plate (F-2) was fired in the ice die with a 10,010 gms explosive charge at a 15-inch standoff. The usual provisions for obtaining the standoff as used in previous large scale closure firings was used. Standoff is obtained by supporting the glass flask in a heavy wall cardboard tube, 8 inches in diameter, with holes drilled through to allow water to flow into the cardboard. During firing, the plate fractured into several large pieces. When examining for the origin of the blank failure, there was evidence that the cardboard tube may have had air trapped in the upper portion next to the glass flask. This may have acted as a high velocity air piston striking the water at the center of the blank and initiating a circular fracture prior to full forming becoming a reality. One piece of steel from the center of the plate had a 180° circular fracture with the same diameter as the cardboard tube standoff. Even though the standoff method had been used on several other tests without adverse results, all previous tests were made using plates of 3/8 or 1/2-inch thick. Thinning measured at the apex portion of the blank which supported the standoff cylinder showed thinning of 26 per cent whereas very little forming had been accomplished in the remainder of the material.

3.3.2.2 The second contour machined plate (F-3) was fired with an explosive charge of 10,010 gms at a standoff of 22 inches. The charge was supported above the blank by a 2-inch x 2-inch wood frame constructed to prevent interference between the explosive charge and the blank to be formed. The blank fractured through the apex after being partially formed and was blown back away from the die cavity -- apparently by the reflected shock from the die cavity. Thickness changes measured in the fractured head are plotted in Figure 23 and tabulated in Table V. The odd pattern of thickness changes illustrates how this blank did not conform to the normal flow pattern established for forming of domes. The diameter change was reduced 10 inches, showing that fracture of the blank occurred early in the forming process.

3.4 REFRIGERATION SYSTEM

The ice die utilized a special refrigeration system which was designed specifically for this program and is described below.

3.4.1 The die refrigeration system consists of three separate units:

- (a) a 10-ton liquid CO₂ storage tank
- (b) a 250-gallon refrigerant (Lexsol) chiller tank
- (c) two copper coil systems to circulate the Lexsol through the inside and outside chambers of the die to be frozen

(See Figure 6)

The liquid CO₂ is expanded into the lower part of the chiller tank by means of a temperature controlled solenoid and a manual CO₂ metering valve. After initial temperature pull-down, the manual metering valve can be closed and a selected temperature maintained by the temperature controller and solenoid. The Lexsol is maintained at -60°F when pumped from the chiller through the copper coil systems in the die.

3.4.2 The procedure for forming the ice die is to invert the die with the plaster mold sealed to the die at the mouth of the draw ring and fill the die cavity from the base plate with water mixed with sawdust. As the water expands, any overflow will occur over the base plate. When the cavity is solid, the base plate is assembled to the die and the die turned for assembling the blank to the draw ring.

3.4.3 Two thermocouples were placed in each of the die chambers; the readings for the two were averaged and recordings made over a period. In Figure 24 are a representative set of such readings covering a period from 24 hours after initiation of refrigeration to complete solidification in the cavity. The consistently lower values for the inside coil may represent the heat absorption by the outer chamber, while it also serves as an insulation to the inner coil system. For the inner coils, temperatures below -30°F have been recorded while the outer coil barely reached a -10°F. Some modifications of the refrigeration system to permit controlled and directional cooling by closer control of the flow and direction of flow could offer better temperature uniformity throughout the die.

3.4.4 Water mixed with wood sawdust was adopted as the die material as a result of a few tests which qualitatively evaluated the shock resistance of ice versus ice mixed with sawdust. The results were very clearly defined to show that the ice mixed with wood sawdust had the ability to maintain its structural integrity much better than the ice alone.

4. PROBLEM AREAS

A number of problem areas have been uncovered during the course of this program which have been described in previous reports as they have occurred, with suggested approaches for the solution. During the course of this period, where a considerable portion of the work was devoted to full scale testing, the problems associated with size have been met. In this section, it is intended to describe all problem areas encountered and the proposed solutions which are offered.

4.1 MATERIALS USED IN ICE DIE FORMING

In the matter of materials for the fabrication of ice dies, it will be absolutely necessary to select a ferrous material with a brittle transition temperature below the freezing point of water. In both the subscale and full scale tests, considerable trouble has been caused by fractures which occur in various parts of the die after every forming shot. This fracturing has been experienced even in the 4-inch thick hold-down ring where previous experiences at ambient temperatures, extending over hundreds of tests, have never shown the hold-down to fail. Initial calculations to determine the feasibility of using insulation materials to protect the AISI 1020 steel from reaching the brittle transition temperature show the insulation approach to be impractical. (See Appendix A). The practical solution lies in selecting a ferrous material which has a low brittle transition temperature. A number of these alloys exist, at a slightly higher cost per pound.

4.1.1 In conjunction with the reduced toughness of some materials at ice temperatures, this condition must also be borne in mind when forming these materials in the ice die. The difficulties which were described above in forming the AISI 1020 steel blanks were a direct result of brittle failure of these blanks. Fortunately, for applications of ice die forming to rocket steels, most of these materials currently in use have a much lower brittle transition temperature than the AISI 1020 steels which have been used in this program.

4.2 PROCUREMENT AND PROCESSING OF ULTRA LARGE STEEL BLANKS

A serious problem area which has made itself manifest during the course of the program is the inability of the mill to supply very large steel sheets to the degree of flatness which will allow surface machining.

The steel ordered was 185-inch diameter, the maximum that the mill could offer, with a mill requirement for minimum thickness of 3/4-inch, which is considerably heavier than actually required. Current experiences in attempting to flatten wavy material have not been too successful. Attempts to pull down the steel stock with a vacuum chuck together with pull-down bolts around the periphery of the blank have not yielded the desired flatness for satisfactory contour machining.

4.2.1 As waviness in the sheet stock is mainly detrimental to surface machining a thickness pattern in the blank, one solution may lie in explosive forming the dome from the blank as supplied by the mill. (Waviness within the limits observed is not a deterrent to explosive forming). The waviness will be eliminated from the material during the forming process. The uniform wall thickness may then be machined in the material after the dome is formed. However, it is highly desirable to have the minimum thickness in which the blank can be furnished in a lighter gauge than is currently specified by the mill for these larger diameters to permit the use of dies of reasonable dimensions to handle these mill-supplied blanks. For example, to form a dome from a 3/4-inch thick blank for eventual machining to several hundred thousands will require a considerably stronger die than for a blank approximately 3/8-inch thick.

4.2.2 An alternate solution, and one which will have specific application to rocket closures larger than the 120-inch diameter, is to fabricate blanks from small individual sheets which can be readily produced by the mills and weld these sheets together. This program has already demonstrated that welded blanks can be explosively formed. The equipment problem for surface machining a thickness pattern can be resolved by surface machining or surface grinding the individual steel sections prior to assembling into a full blank. The complexity of grinding or machining the individual sections of a full blank is more than compensated for by the array of available equipment which can handle this operation. Distortions incurred due to welding will have no effect on the assembly of the blank to the die or on explosive forming of the blank.

4.3 TRANSPORTATION OF LARGE BLANKS

In transporting 185-inch diameter blanks by rail and truck, the upper limits of dimensional clearances for tunnels and overpasses are being approached. Special clearances for travel are necessary. Obviously, any extension in blank diameter -- as will be required for rockets

larger than 120 inch -- will make it impossible to transport the full blank as a unit. It is apparent that the blank must be supplied to the fabrication area in individual sections and welded into a full blank at that point. Provisions for trimming the blank at that point will also be necessary to keep the dimensions of the formed unit as small as possible, consistent with the final required dimensions.

5. CONCLUSIONS

As a result of the work completed to date, some preliminary conclusions may be expressed with reference to the explosive forming process as related to large rocket motor closures.

5.1 The explosive forming process has a valuable contribution to make in the fabrication of large rocket motor closures. The ability to form high strength steel alloys from blanks made up of sections, welded together, and the practicality of making the necessary preparatory operations (machining and grinding) in the individual sections to eliminate the major portion of final machining in the formed head give the explosive forming technique a wide advantage over other possible approaches.

5.2 The use of the free forming die or ice cavity die to produce large hemispherical closures to close thickness and contour tolerances has not been satisfactorily demonstrated. In the subscale version (36-inch diameter), a maximum contour deviation from a hemisphere of 0.100-inch to 0.125-inch has been shown with the ice die. This has not been readily reproduced, and has not yet been produced in the full scale.

5.3 The ice die cannot be used to form a blank where wrinkling may be anticipated. If sandwiching will overcome the wrinkling, the die should be designed to accommodate sandwiching. Where, in hard dies, moderate wrinkling was not considered a problem as the condition could be corrected in a subsequent sizing shot, in ice dies, wrinkling during forming will destroy the value of the die as the ice cavity will not resist the concentrated pressure exerted by the material as it is producing a wrinkle.

5.4 It is better to use smaller steel sheets which the mills can produce to close thickness dimensions and minimal waviness and weld a number together to form one large blank than to have the mill fabricate one large integral blank to thicknesses which the mill will specify and with waviness that precludes further processing.

5.5 Because of the necessity for progressive forming with at least one intermediate anneal to produce a full hemisphere, it is considered highly desirable that the 1.4:1 or 1.6:1 elliptical contour be considered as an acceptable contour for these large rocket motor closures. In the current program, this design change may incur some delays in the fabrication of the plaster mold to give this configuration, but the increased probability for success would appear to justify the delay which the change entails.

5.6 A finite advantage of the ice die over the free forming approach has not been quantitatively demonstrated. Because of the relative simplicity of free forming and the economies available, this approach must be examined further in a more basic fashion and developed into a true production process.

6. FUTURE WORK

6.1 Within the time remaining on this program, emphasis will be placed on the fabrication of the two 120-inch diameter closures in AMS 6434 steel. The Project Officer will be consulted on the advisability of redirecting the effort to produce a 1.6 to 1 or a 1.4 to 1 elliptical contour. This will entail a new plaster mold, but no other changes will be necessary.

6.2 With the 36-inch diameter die, the free forming approach will be investigated further in terms of the elliptical contour in lieu of the hemisphere.

6.3 Specific information developed in current work and which is directly applicable to the production of 160-inch diameter closures will be collated and assembled in preparation for final reporting.

TABLE I

TABULATION OF TEST CONDITIONS AND RESULTS

Test No.	Type of Die	Die Condition	Material (Steel)	Firing No.	Explosive Charge (gms)	Standoff (in.)	Nominal Thickness (in.)	Defl. (in.)	Remarks
WHS-3	36-INCH SUBSCALE	ICE	AMS 6434 WELDED	1st	3,300	7	1/4	18	Good contour - will stress relieve and refire.
WHS-3				2nd	462	19	1/4	-	Maximum deviation of 3/8" from hemispherical contour - will refire.
WHS-3				3rd	594	18-1/2	1/4	-	Maximum deviation of .125" from hemispherical contour.
HS 1/4-1			AMS 6434	1st	3,520	7	1/4	17-1/8	Bottomed in ice die.
P-14		FREE FORM	AISI 1020	1st	2,750	7	5/16	-	Air cushion caused blank to fracture.
HS 1/4-2		ICE	AMS 6434	1st	3,530	7	1/4	17-1/2	1 wrinkle - will stress relieve and refire.
HS 1/4-2				2nd	713	19	1/4	18-1/8	Flat apex. Over-formed in skirt area.
HS 1/4-3				1st	3,520	7	1/4	18	1 wrinkle - will stress relieve to refire.
HS 1/4-3				2nd	713	19	1/4	18-1/2	Contour in apex slightly flat. Some overforming in skirt area.
HS 1/4-4				1st	3,520	7	1/4	18	Wrinkles on the contour protruding outward.
HS 1/4-5				1st	3,520	7	1/4	18	Will stress relieve and refire.
HS 1/4-5				2nd	824	19	1/4	-	Came out of die during firing.
HS 1/4-5				3rd	353	19	1/4	-	Poor contour - will refire.
F-1	120-INCH FULL SCALE	FREE FORM	AISI 1020	1st	12,100	15	1/2	37-1/2	Came out of die. Slightly egg-shaped Poor contour.
F-1				2nd	10,010	55	1/2	48-1/2	Will be stress relieved and refired.
F-2		ICE		1st	10,010	15	.150	-	Refired. Dome formed well.
F-3				1st	10,010	22	.130	-	Broke into several pieces. Split through the apex.

TABLE II

STRAIN READINGS - AISI 1020 STEEL
F-1 FULL SCALE, FIRST FIRING

RADIAL				TANGENTIAL			
Average Before Firing (in.)	Average After Firing (in.)	Amount of Change (in.)	% Change	Average Before Firing (in.)	Average After Firing (in.)	Amount of Change (in.)	% Change
APEX				APEX			
10.000	11.000	1.000	10.00	10.000	10.843	.843	8.43
10.000	10.875	.875	8.75	10.000	10.781	.781	7.81
10.000	10.843	.843	8.43	10.000	10.687	.687	6.87
10.000	10.718	.718	7.18	10.000	10.437	.437	4.37
10.000	10.562	.562	5.62	10.000	10.000	0	0
10.000	10.656	.656	6.56	10.000	9.468	-.531	-5.31
10.000	10.531	.531	5.31	10.000	8.687	-1.312	-13.12
10.000	10.812	.812	8.12	10.000	8.906	-1.093	-10.93
10.000	10.687	.687	6.87	10.000	9.093	-.906	-9.06
FLANGE				FLANGE			

TABLE III

THICKNESS DATA - FIRST FIRING F-1
120-INCH FULL SCALE PLATE
AISI 1020 STEEL

Average Before (in.)	Average After (in.)	Amount of Change (in.)	Per cent Change
Apex .523	.415	-.108	-20.6
.525	.431	-.094	-17.9
.526	.437	-.089	-16.9
.525	.447	-.078	-14.8
.525	.463	-.062	-11.8
.526	.487	-.039	-7.4
.524	.502	-.022	-4.2
.510	.484	-.026	-5.1
.508	.522	+.014	+2.4
.508	.526	+.018	+3.1

TABLE IV

THICKNESS DATA OF
CONTOUR MACHINED AISI 1020 STEEL PLATES
(FULL SCALE)

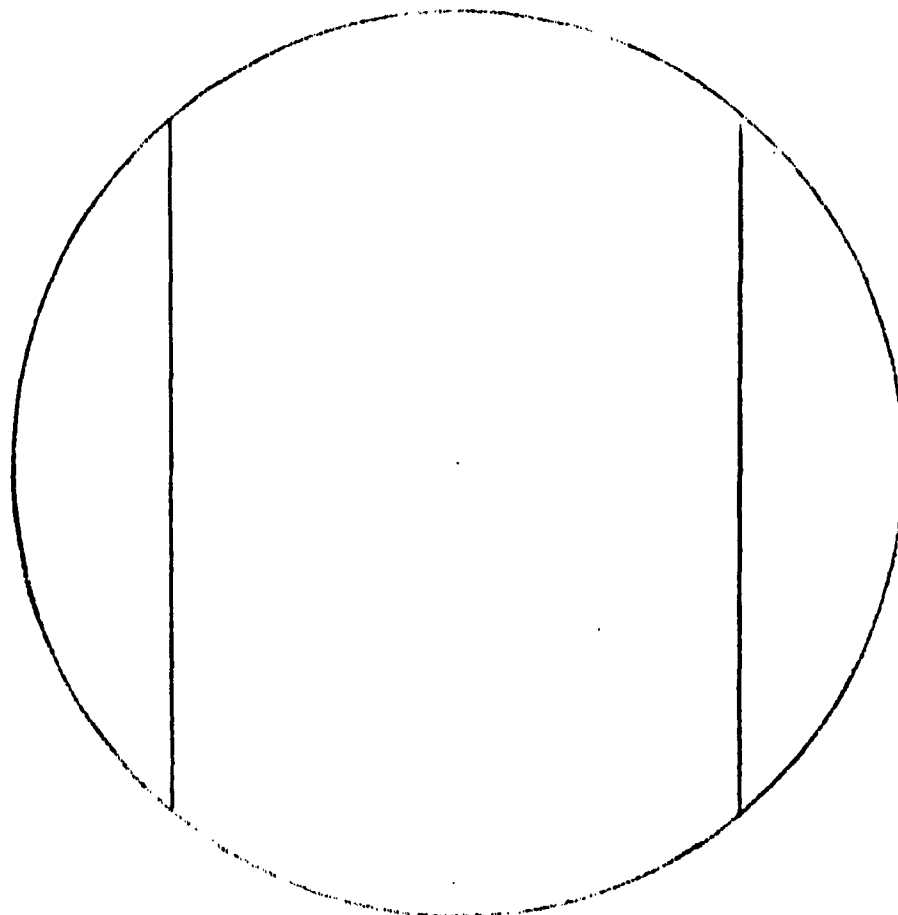
Distance From Apex (in.)	Desired Thickness (in.)	Thickness (F-2) Contoured Plate (in.)	Thickness (F-3) Contoured Plate (in.)
0	. 185	. 165	. 120
10	. 185	. 163	. 141
20	. 182	. 168	. 140
30	. 178	. 157	. 131
40	. 174	. 154	. 132
50	. 170	. 151	. 139
60	. 166	. 148	. 134
70	. 162	. 144	. 127
80	. 290	. 170	. 306
90	. 340	. 283	. 325

TABLE V

THICKNESS DATA
120-INCH FULL SCALE FIRING F-3*
AISI 1020 CONTOUR MACHINED PLATE

Average Before (in.)	Average After (in.)	Amount of Change (in.)	Per cent Change
Apex .120	.107	-.013	-9.2
.141	.115	-.026	-18.4
.140	.112	-.028	-20.0
.131	.108	-.023	-17.5
.132	.112	-.020	-15.1
.134	.117	-.017	-12.7
.139	.116	-.023	-16.5
.134	.131	-.003	-2.2
.127	.132	+.005	+3.9
.307	.314	+.007	+1.9
.325	.331	+.006	+1.8

* Split during forming.



**Figure 1. Weld Pattern Used for AISI 1020 Full Scale
(185-Inch Diameter) and AMS 6434 Subscale
(56-Inch Diameter) Steel Blanks**

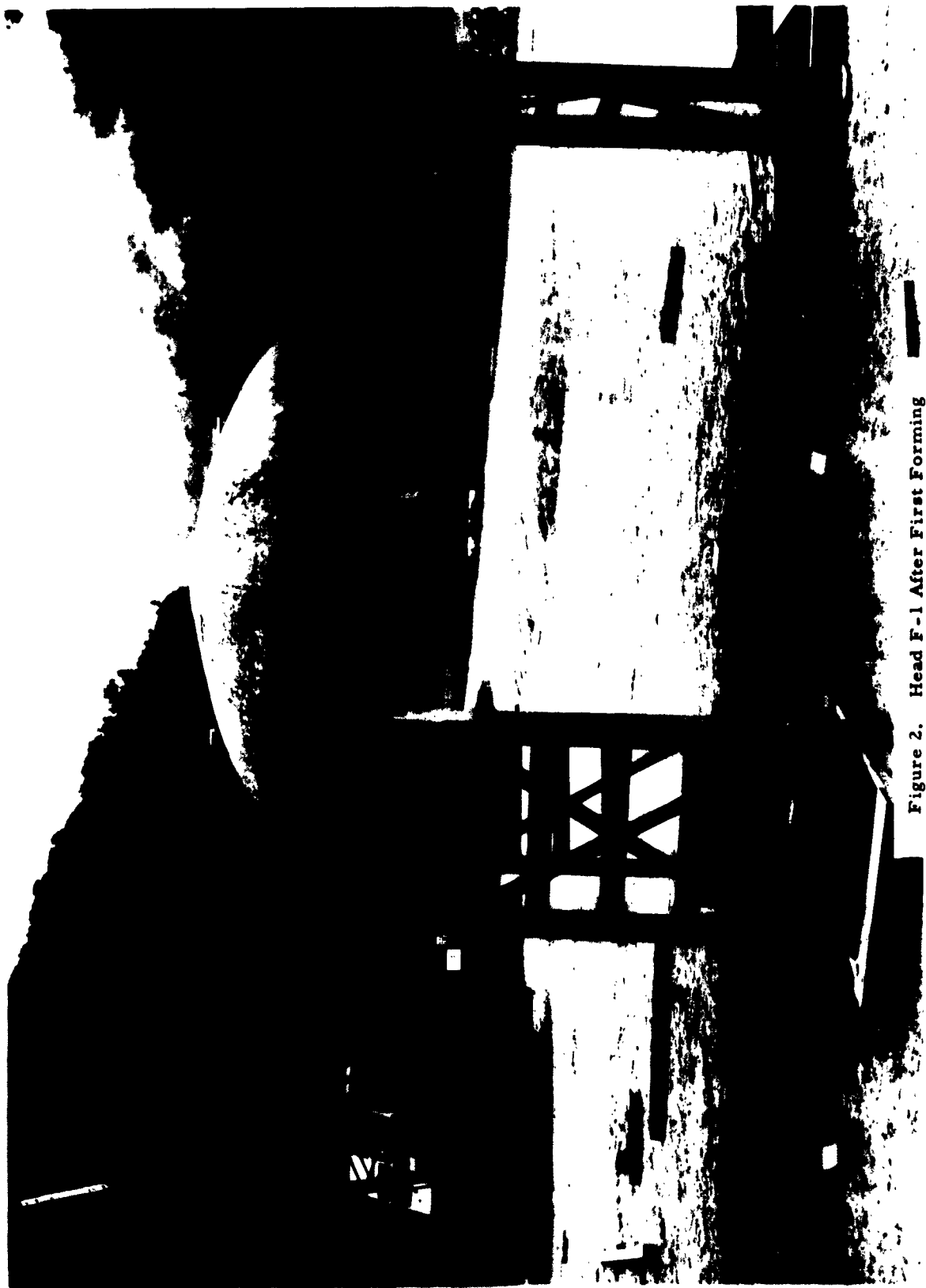


Figure 2. Head F-1 After First Forming

STRAIN MEASUREMENTS FOR FULL SCALE AISI 1020 STEEL

F-1 (FIRST FIRING)

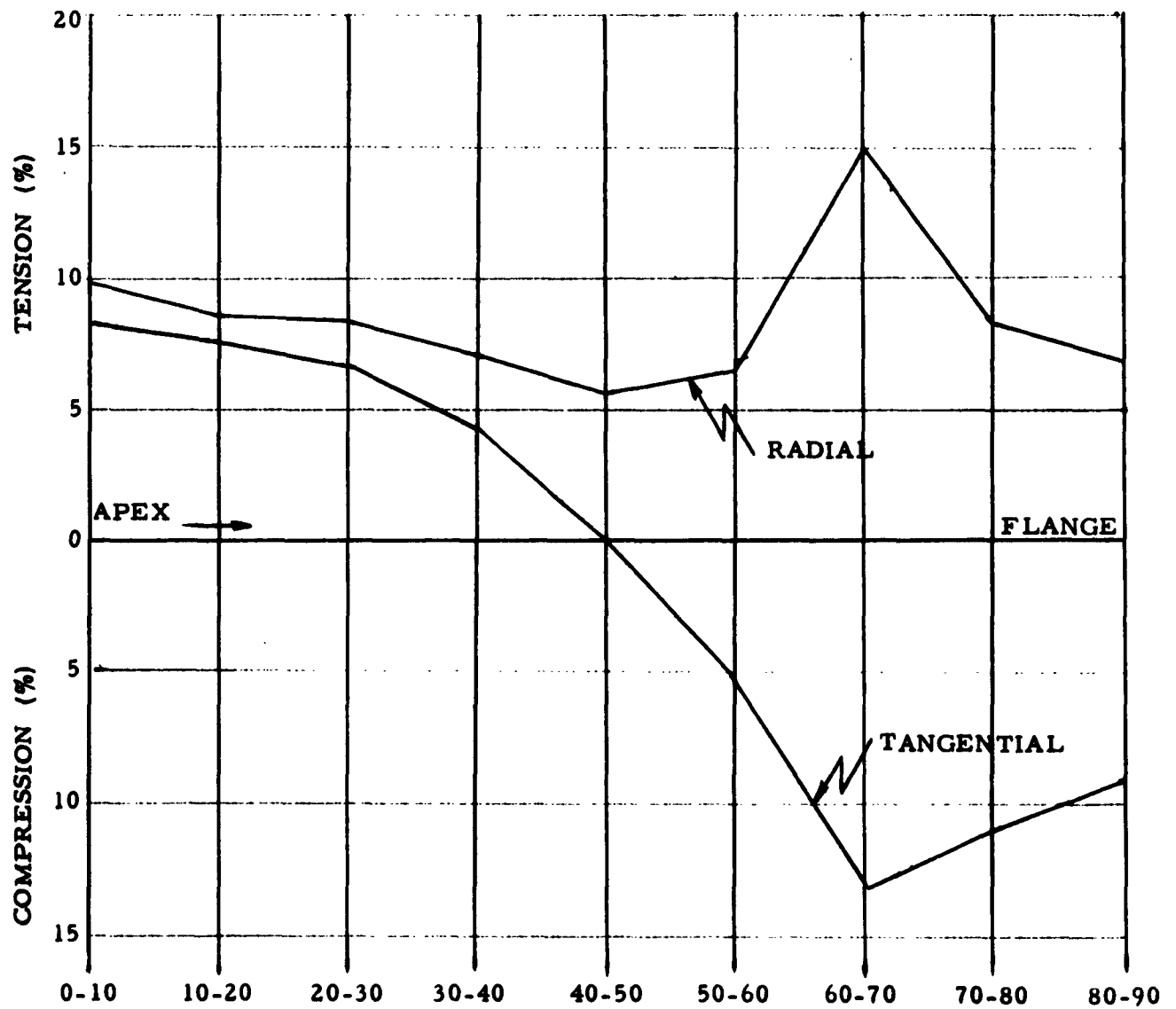


Figure 3

THICKNESS DATA - AISI 1020 STEEL
F-1 (BEFORE AND AFTER FIRST FIRING)

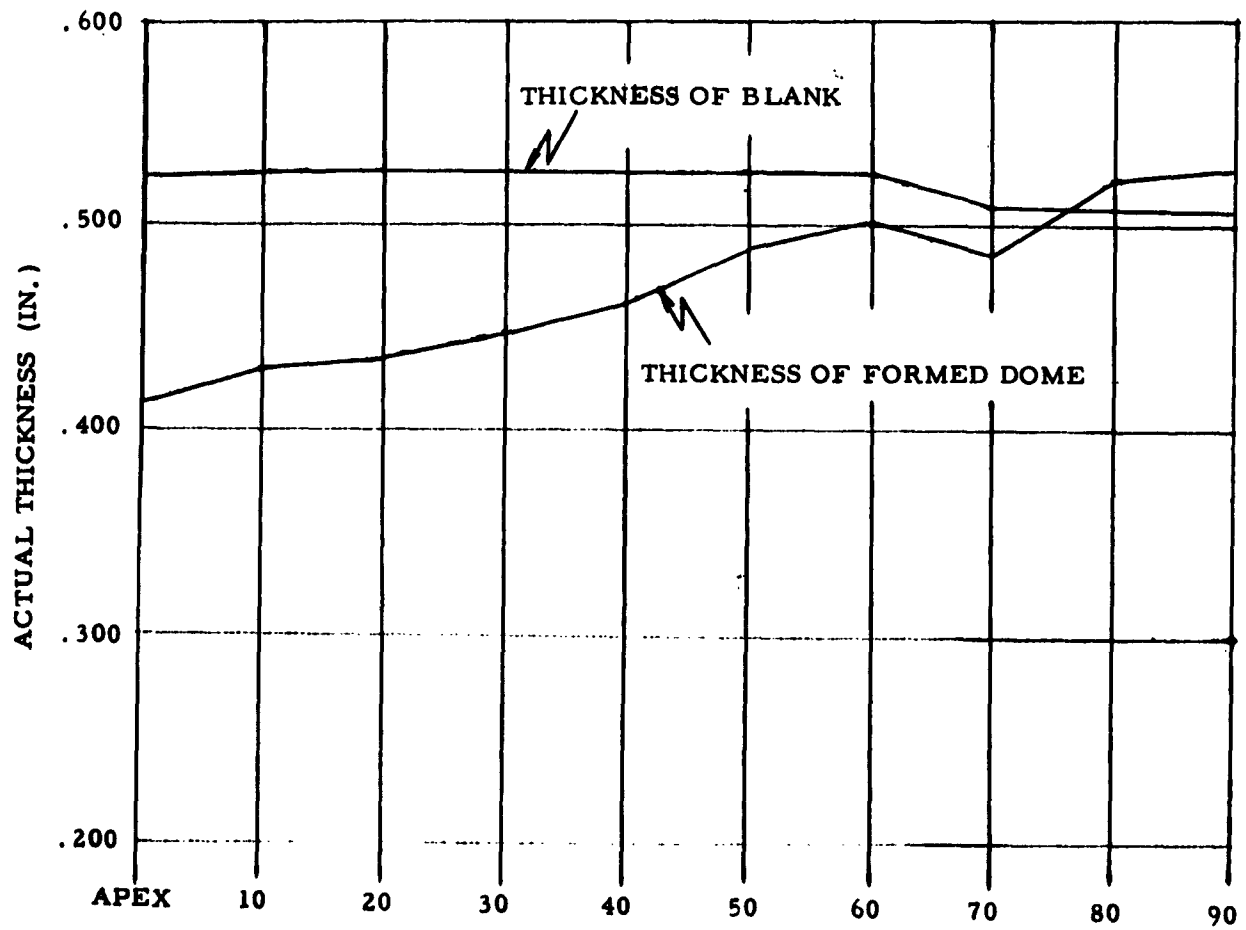


Figure 4

THICKNESS CHANGE
FULL SCALE AISI 1020 STEEL BLANK
F1 (FIRST FIRING)

(Plotted From Table III)

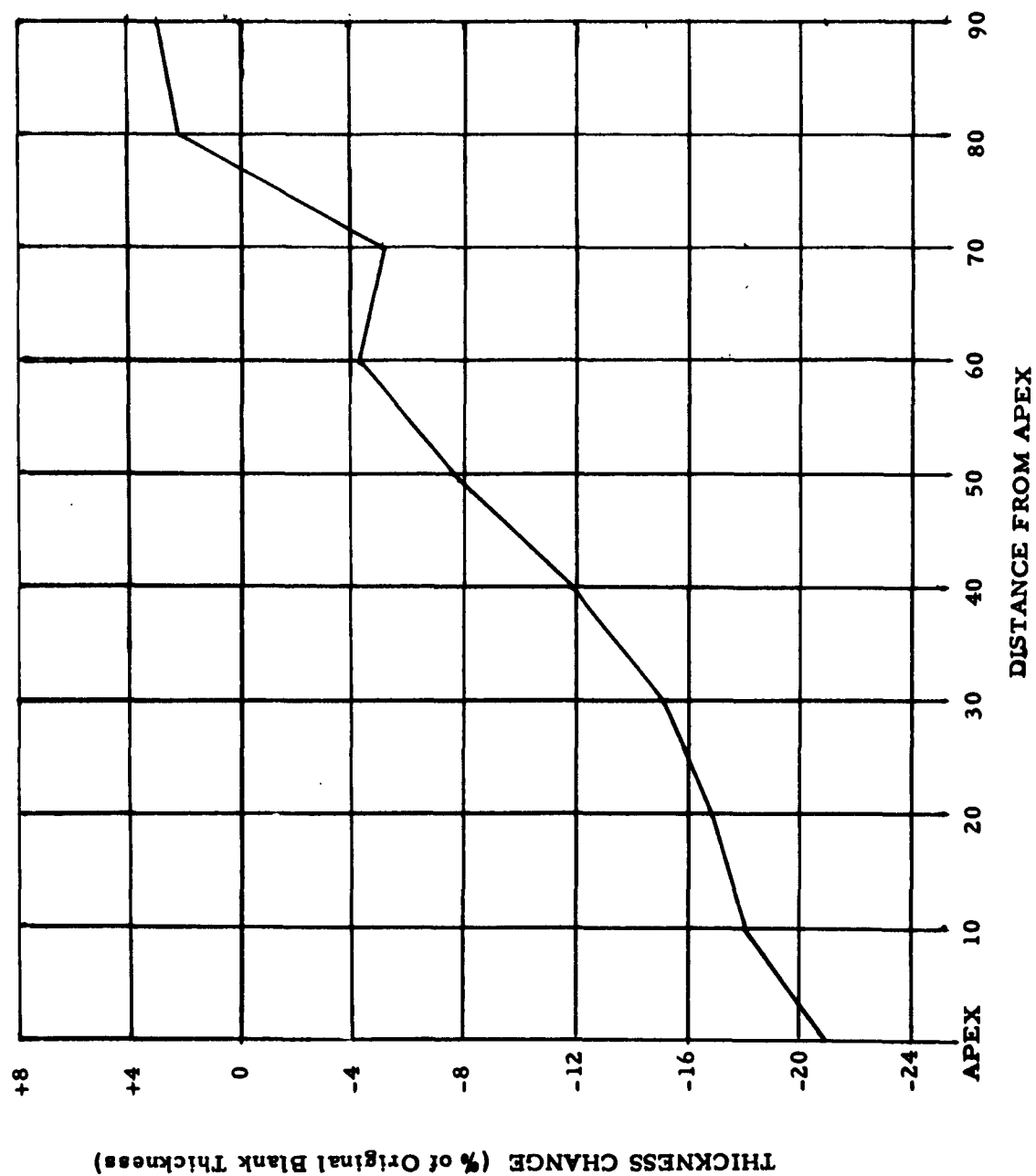


Figure 5

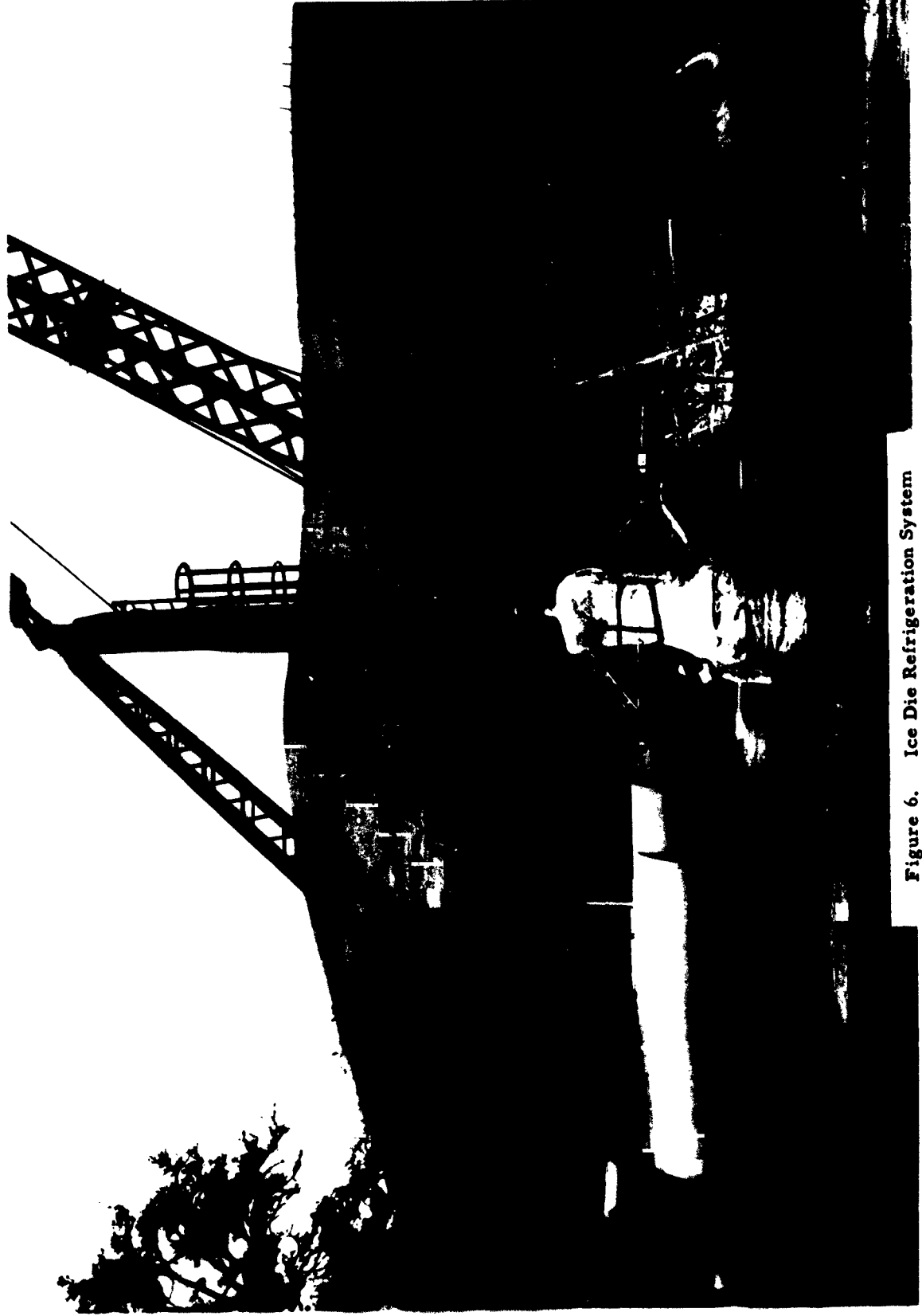


Figure 6. Ice Die Refrigeration System



Figure 7. Removing Plaster Mold From Die Cavity



Figure 8. Ice Die Cavity



Figure 9. Preparing Head For Assembly Into Die

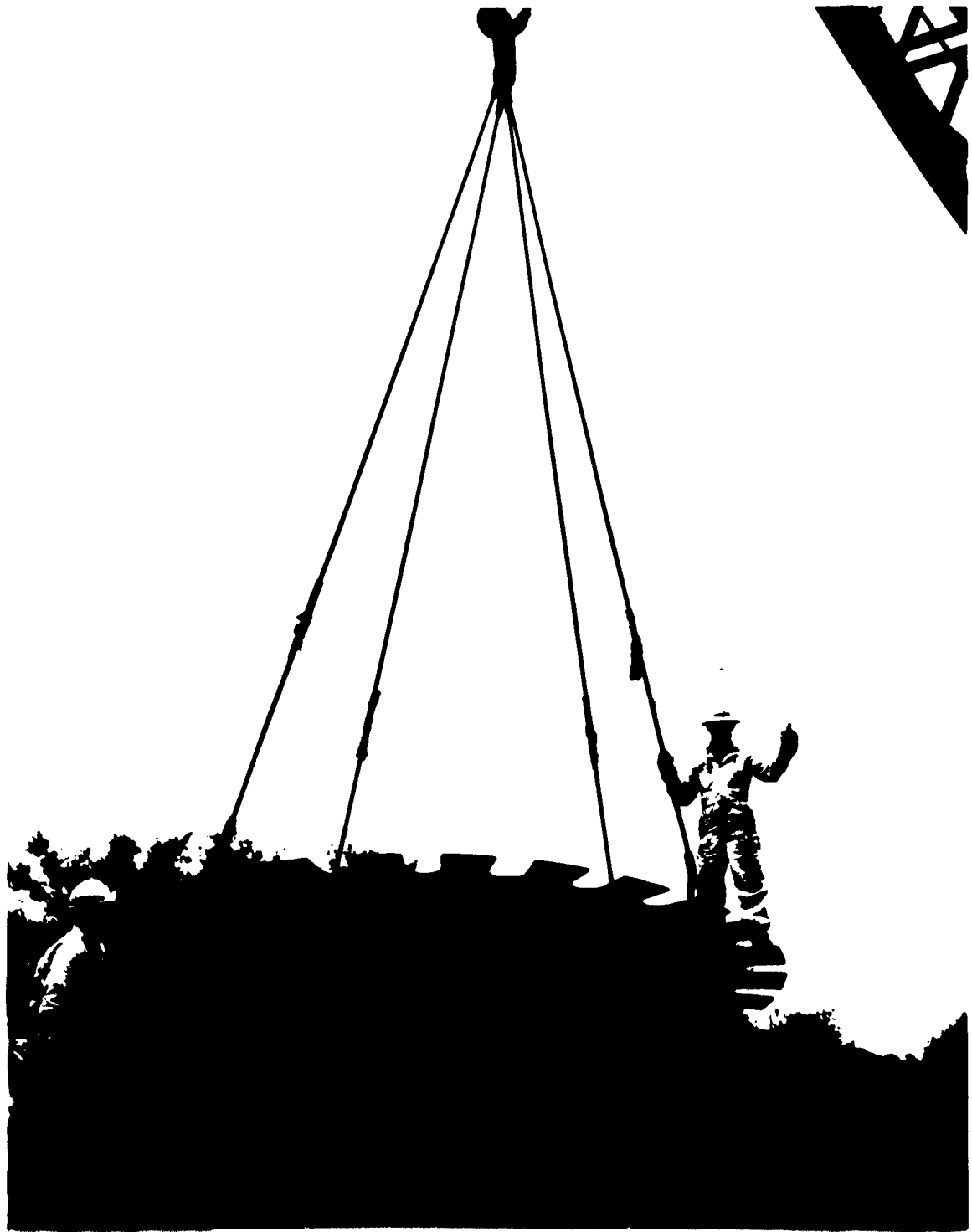


Figure 10. Loading Head Into Die Cavity

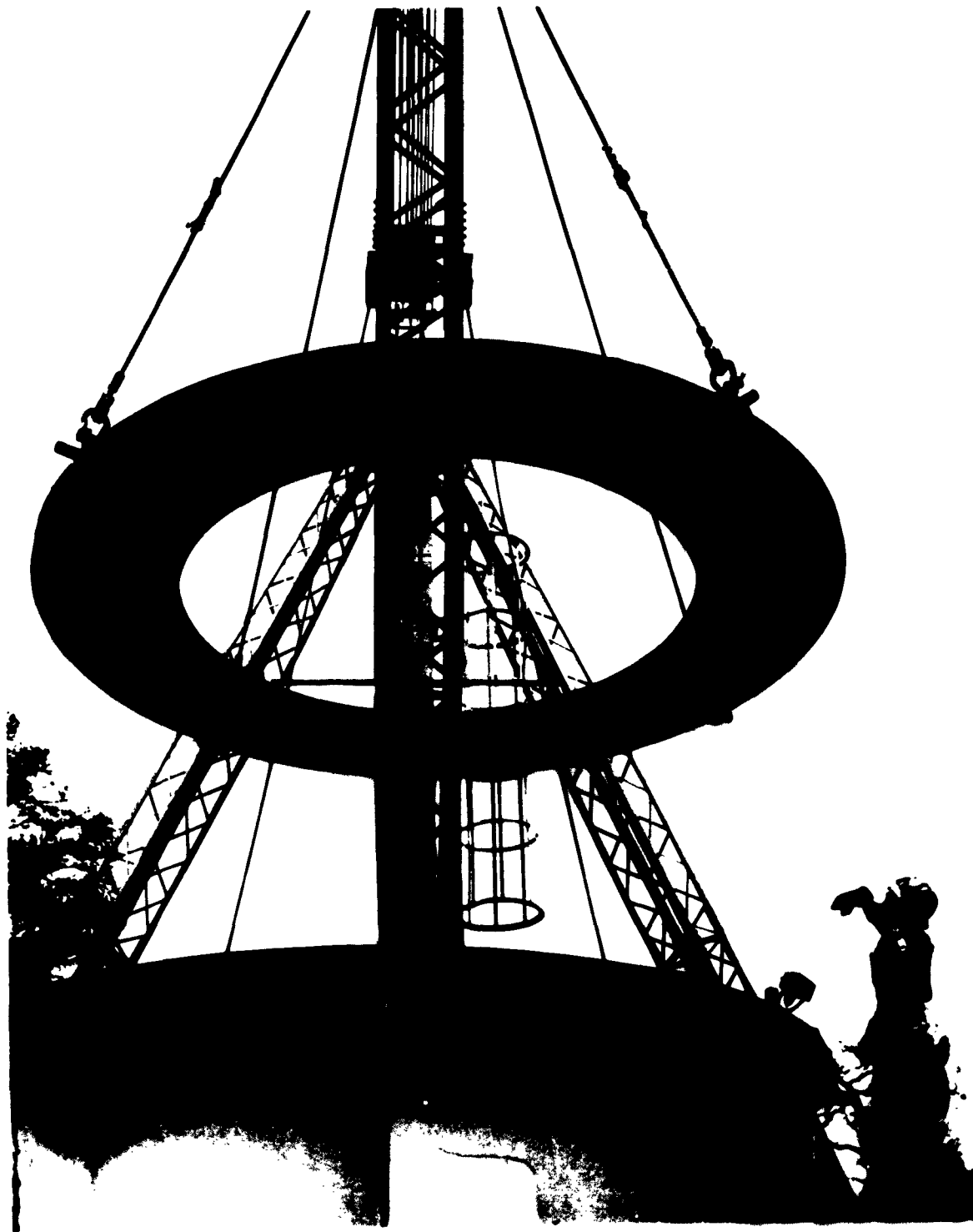


Figure 11. Assembly of Hold-Down Ring

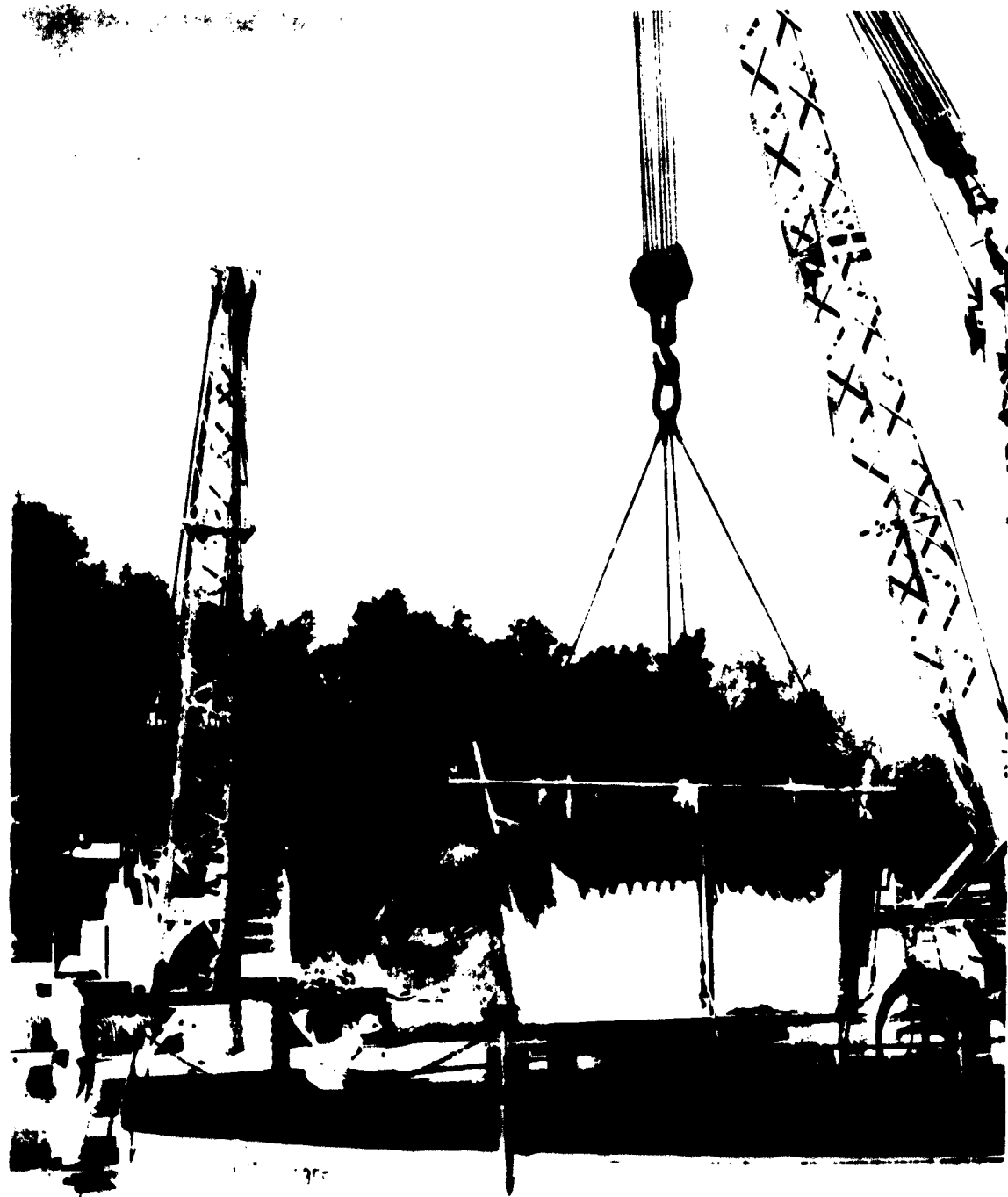


Figure 12. Fully Assembled Die

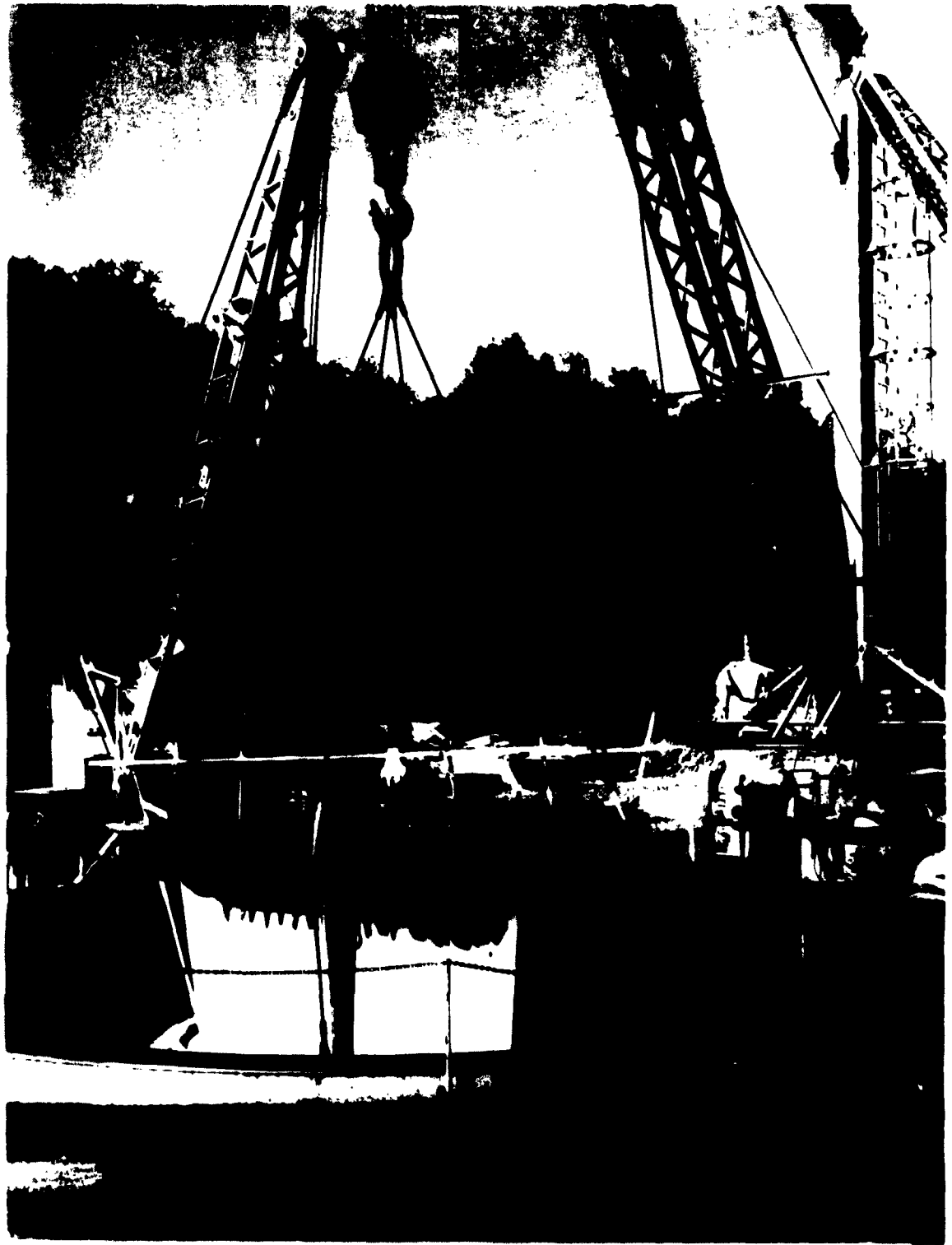


Figure 13. Lowering Die Into Water Tank

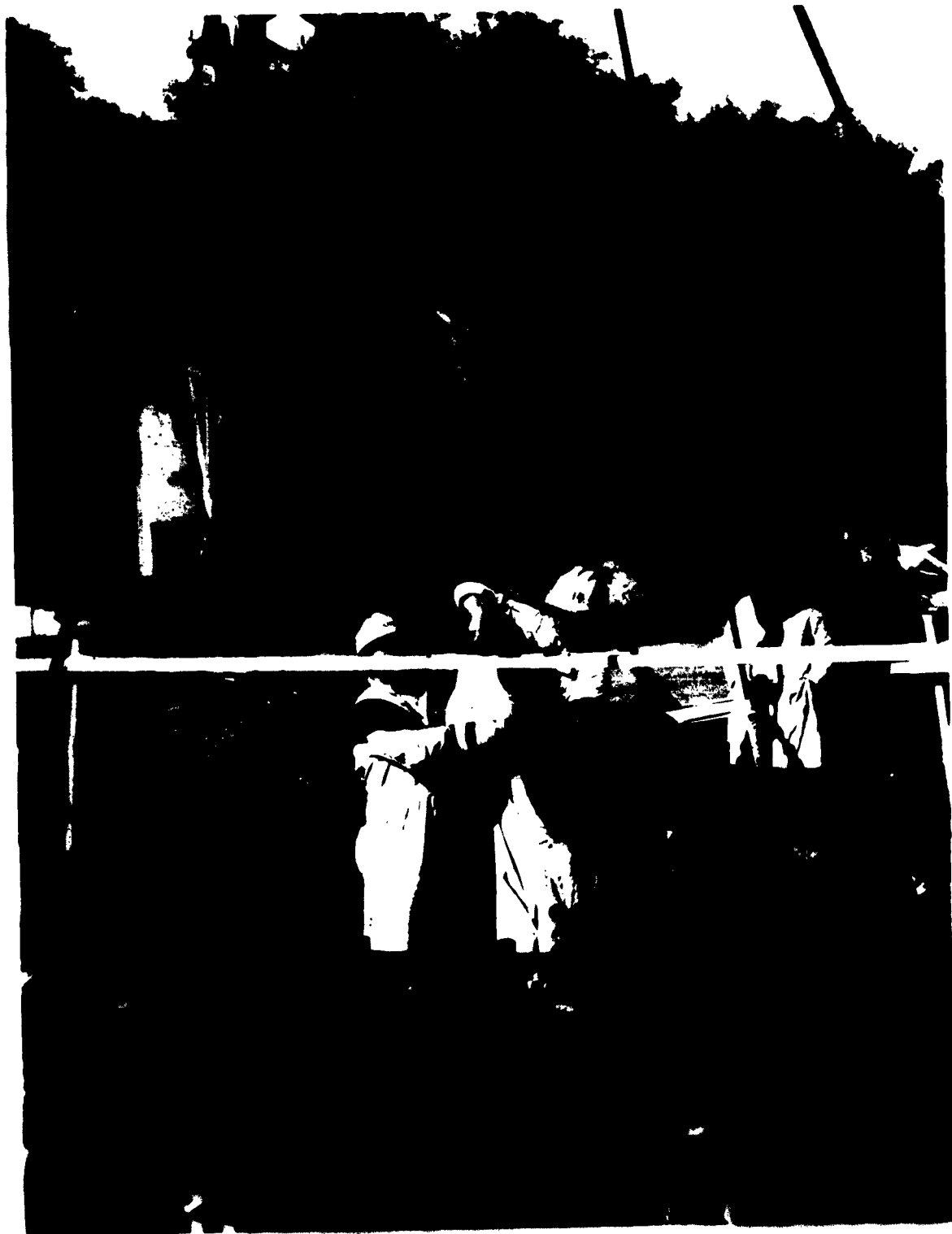


Figure 14. Pouring and Assembling Explosive Charge



Figure 15. Water Spray From Full Scale Firing



Figure 16. Removing Die From Forming Tank



Figure 17. Water Being Removed From Formed Head

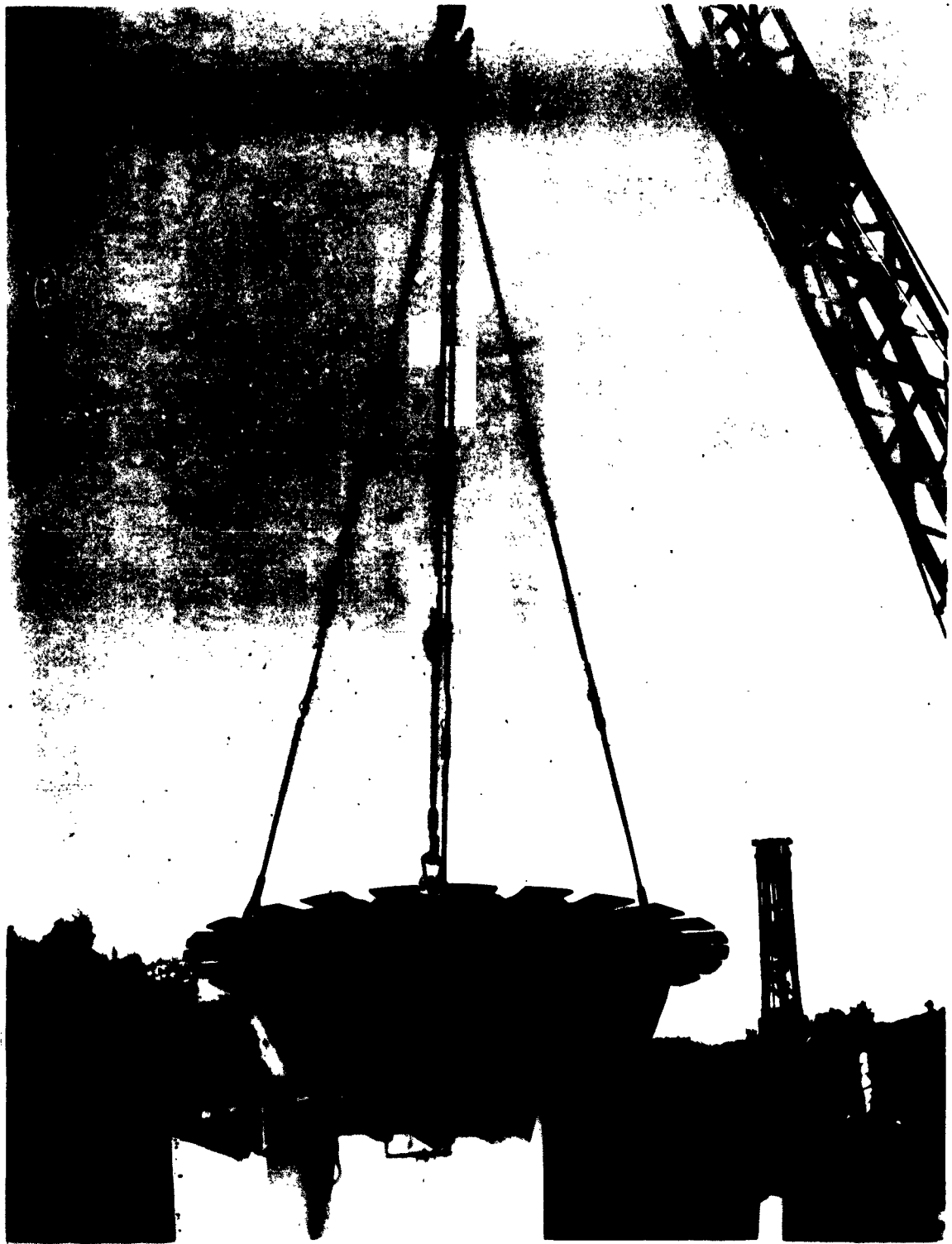


Figure 18. Removing Head F-1 From Die After Second Firing

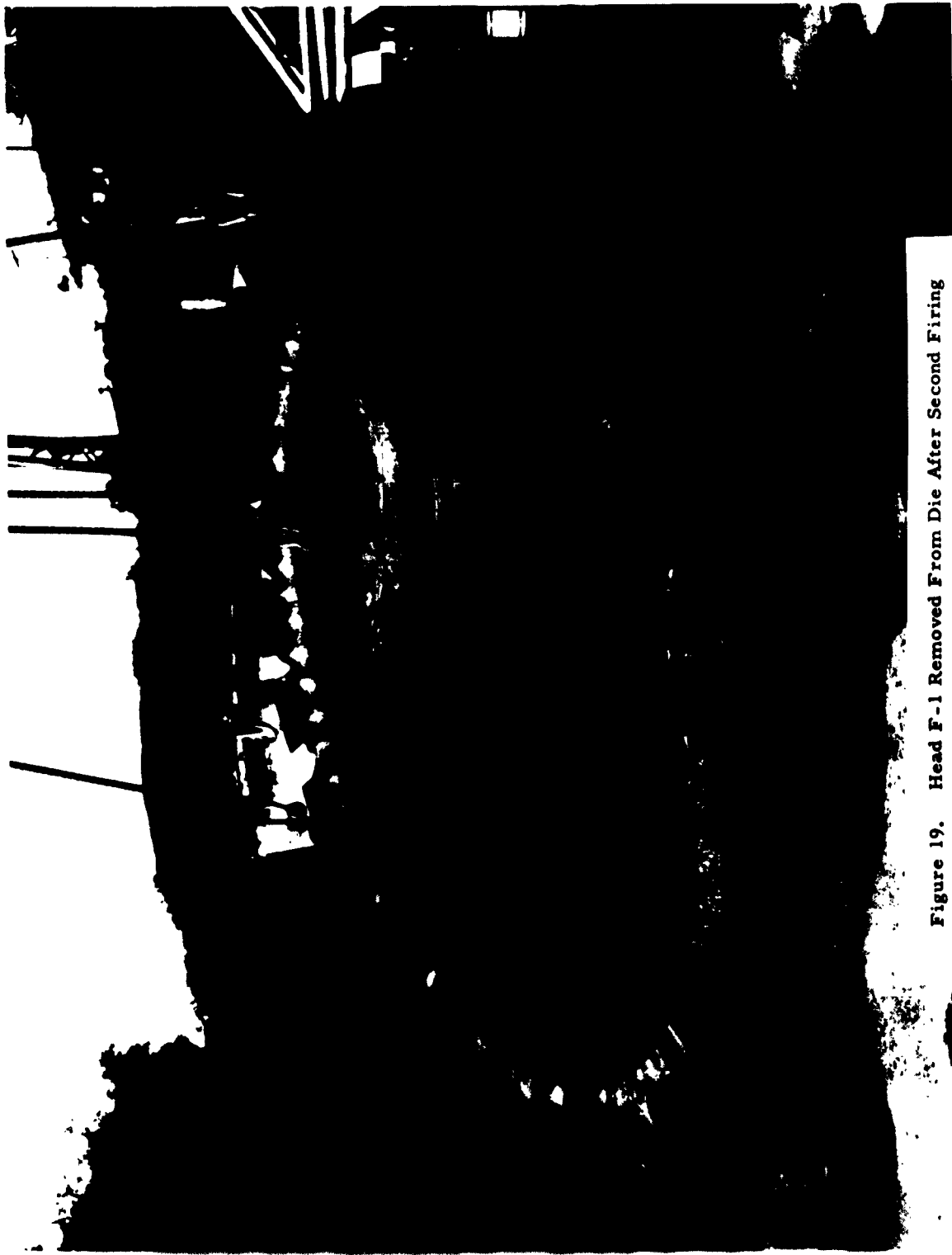


Figure 19. Head F-1 Removed From Die After Second Firing



Figure 20. Side View of Head F-1 After Second Firing

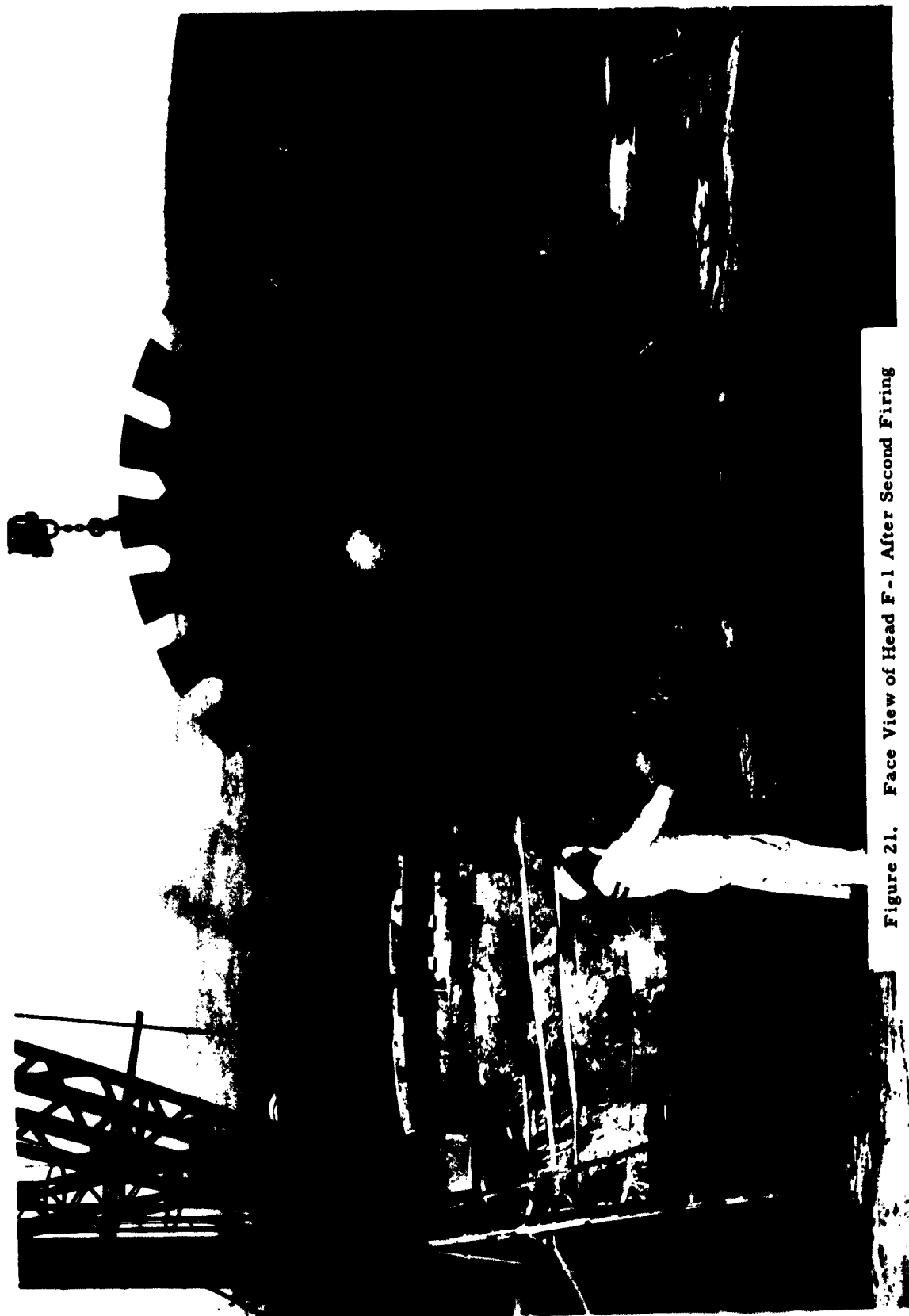


Figure 21. Face View of Head F-1 After Second Firing



Figure 22. Head F-1 with Refrigeration System and Die in Background

THICKNESS CHANGE
 AISI 1020 CONTOUR MACHINED STEEL BLANK
 F3 (FIRST FIRING)

(Plotted From Table V)

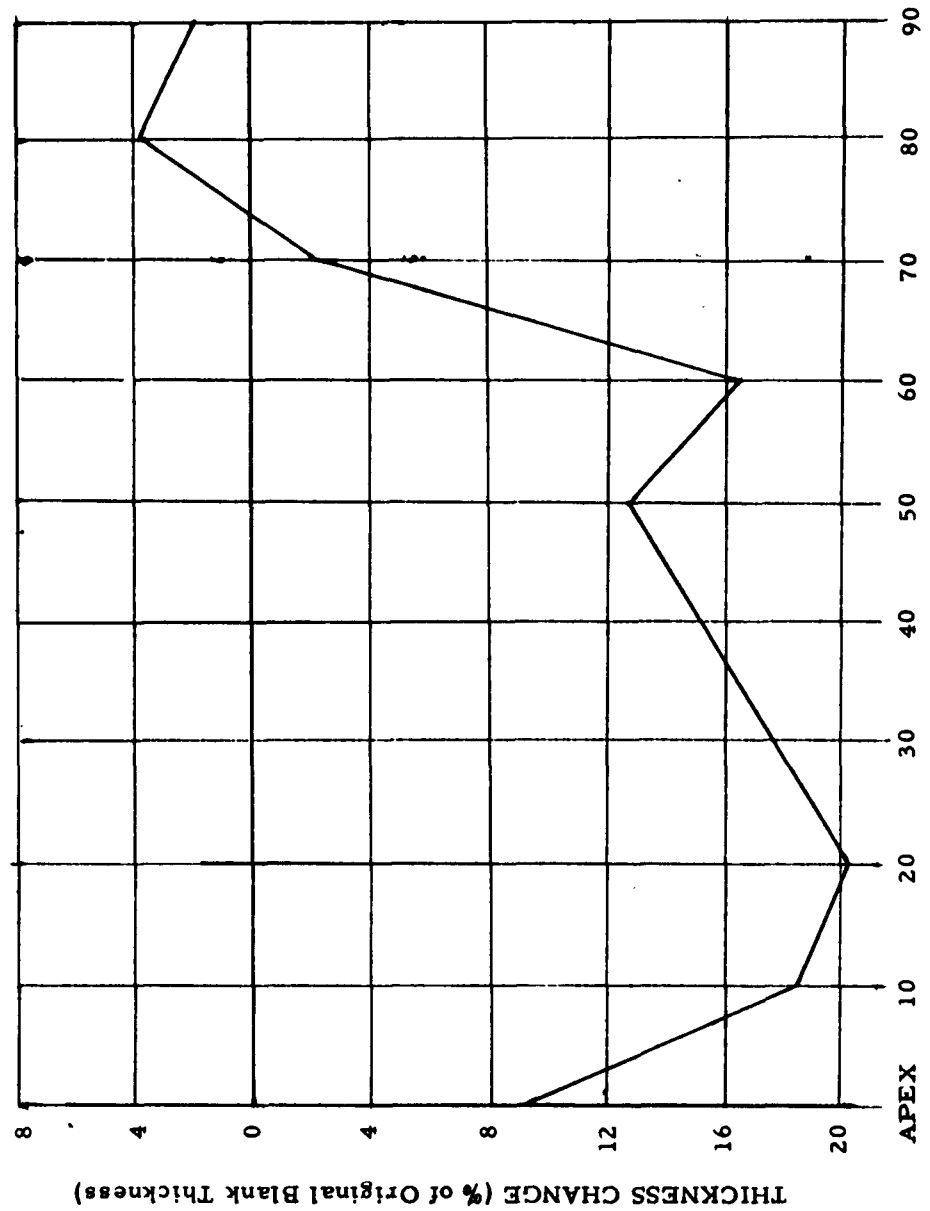


Figure 23

AVERAGE TEMPERATURE OF THERMOCOUPLES FOR
INSIDE AND OUTSIDE COIL SYSTEMS OF THE FULL SCALE ICE DIE

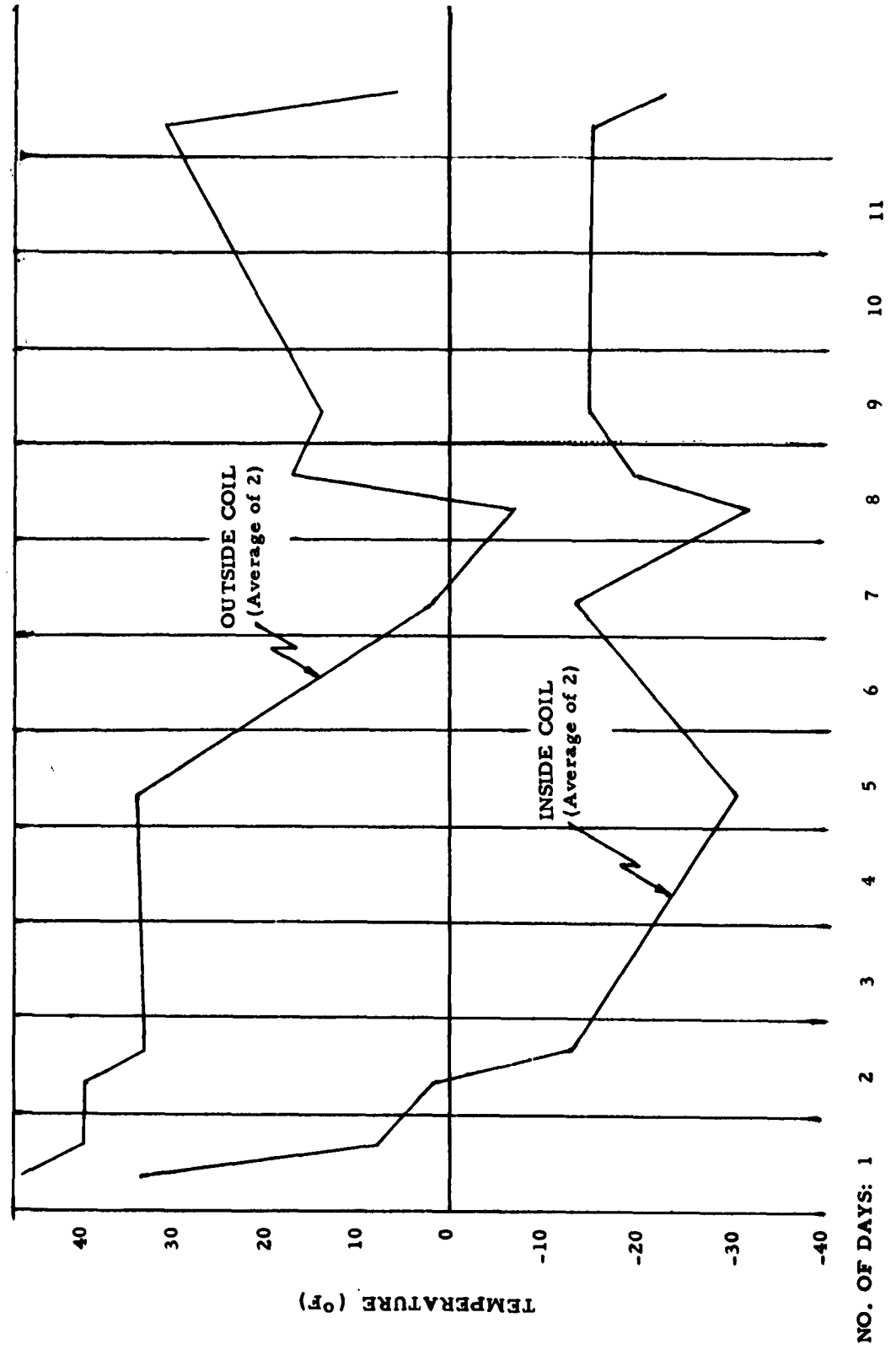


Figure 24

APPENDIX A

CALCULATIONS TO DETERMINE THE EFFECTIVENESS OF INSULATION IN ICE FORMING DIES TO INCREASE THE TEMPERATURE AT THE DIE-BLANK INTERFACE

For conduction of heat through a composite plane wall at steady state conditions:

$$Q = \frac{A (t_o - t_3)}{h_o + \frac{L_1}{K_1} + \frac{L_2}{K_2}},$$

$$t_2 - t_3 = \frac{QL_2}{K_2 A}$$

$$t_1 - t_2 = \frac{QL_1}{K_1 A}$$

Where: $Q = \text{BTU/Hr}$

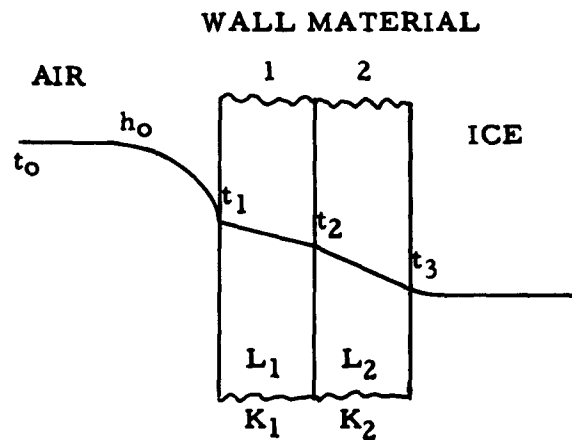
$A = \text{Ft}^2$

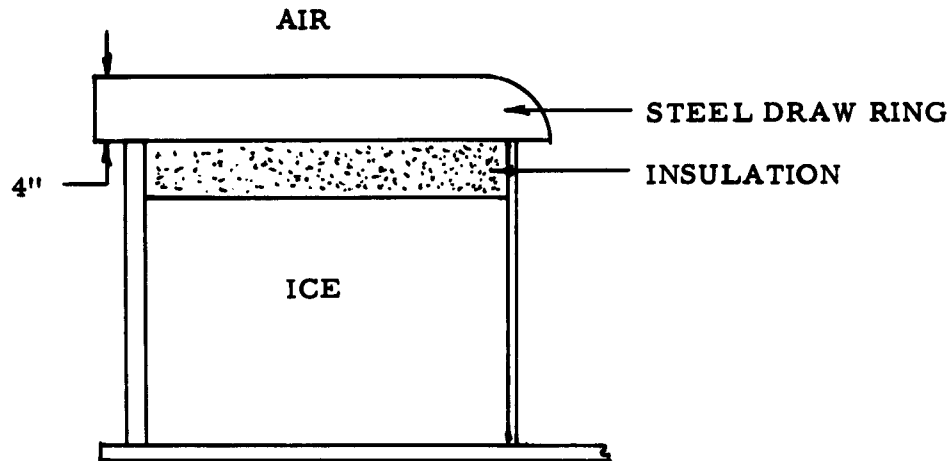
$h = \text{BTU/Ft}^2 \cdot ^\circ\text{F} \cdot \text{Hr}$

$L = \text{In}$

$K = \text{BTU} \cdot \text{In/Ft}^2 \cdot ^\circ\text{F} \cdot \text{Hr}$

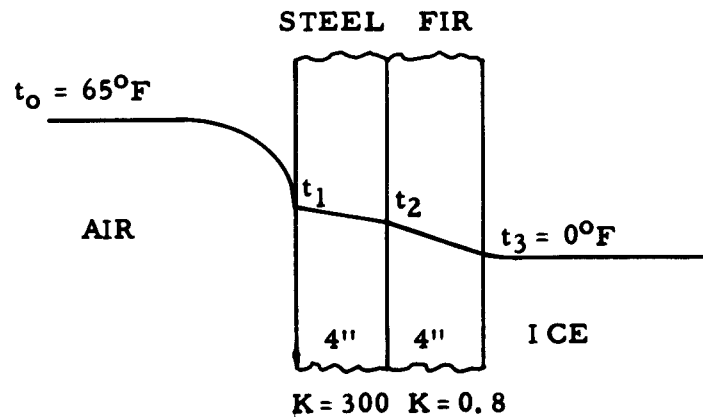
$t = ^\circ\text{F}$





ASSUME: Ice Temperature at Wall = 0°F
 Air Temperature = 65°F
 Steel, $K = 300 \text{ BTU-In/Ft}^2 - ^{\circ}\text{F} - \text{Hr}$
 Fir, $K = 0.8 \text{ BTU-In/Ft}^2 - ^{\circ}\text{F} - \text{Hr}$
 Rock Wool, $K = 0.27 \text{ BTU-In/Ft}^2 - ^{\circ}\text{F} - \text{Hr}$

CALCULATION 1 4" FIR INSULATION



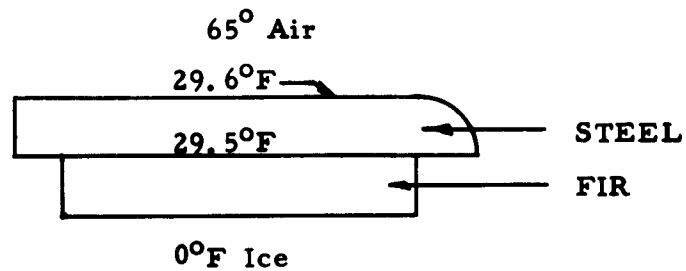
Consider Unit Area:

$$Q = \frac{A (t_o - t_3)}{h_o + \frac{L_1}{K_1} + \frac{L_2}{K_2}} = \frac{1 (65 - 0)}{6 + \frac{4}{300} + \frac{4}{0.8}} = \frac{65}{6 + 0.0133 + 5} = \frac{65}{11.03}$$

$$= 5.90 \text{ BTU/Hr} - \text{Ft}^2$$

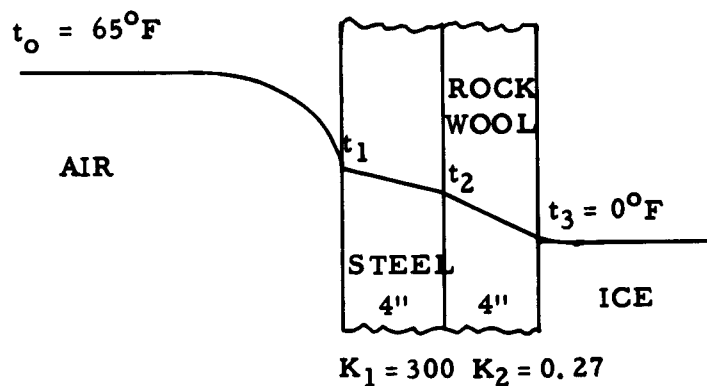
$$t_2 = t_3 + \frac{QL_2}{K_2 A} = 0 + \frac{5.90 \times 4}{0.8 \times 1} = 29.5^\circ\text{F}$$

$$t_1 = t_2 + \frac{QL_1}{K_1 A} = 29.5 + \frac{5.90 \times 4}{300 \times 1} = 29.5 + 0.0785 = 29.6^\circ\text{F}$$



CALCULATION 2

4" ROCK WOOL INSULATION

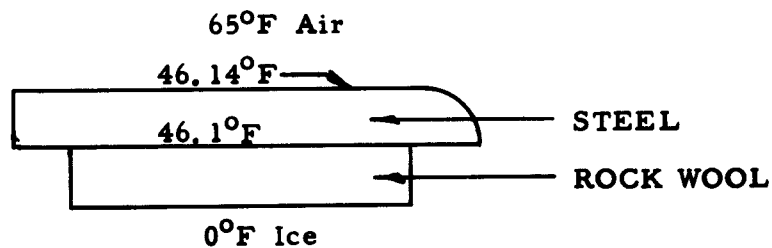


Consider Unit Area:

$$Q = \frac{A (t_o - t_3)}{h_o + \frac{L_1}{K_1} + \frac{L_2}{K_2}} = \frac{1 (65 - 0)}{6 + \frac{4}{300} + \frac{4}{0.27}} = \frac{65}{6 + 0.0133 + 14.8} = \frac{65}{20.81} = 3.12 \text{ BTU/Hr-Ft}^2$$

$$t_2 = t_3 + \frac{QL_2}{K_2 A} = 0 + \frac{3.12 \times 4}{0.27 \times 1} = 46.1^\circ\text{F}$$

$$t_1 = t_2 + \frac{QL_1}{K_1 A} = 46.1 + \frac{3.12 \times 4}{300 \times 1} = 46.1 + 0.0415 = 46.14^\circ\text{F}$$



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